Correlated X-ray spectral and fast-timing behaviour of 4U 1636−53

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Abstract. We present a study of the persistent X-ray emission from the low-mass X-ray binary 4U 1636−53 based on the entire archival EXOSAT ME data set. We performed a homogeneous analysis of all five EXOSAT observations in terms of the correlated rapid X-ray variability and X-ray spectral properties by means of power spectra, and colour-colour and hardness-intensity diagrams, respectively. Over the years we find similar patterns in the colour-colour diagram and the hardness-intensity diagram, but small shifts in their positions occur. We find one case of an island-banana transition. On all but one occasion the differences in colours are smaller than 5 %. Between the two "island state" data sets we find a shift of 8 % in the soft colour, which must be at least partly intrinsic.

Clear correlations are present between the X-ray colours (which are governed by the mass accretion rate) and the power spectrum. With increasing mass accretion rate the fractional rms amplitude of the power-law shaped power spectral component that dominates the power spectra below ∼ 1 Hz rises, while the band-limited noise component at higher frequencies drops. The cut-off frequency of the band-limited component increases when its amplitude decreases. This is reminiscent of the behaviour of black-hole candidates in the low state.

Key words: accretion, accretion disks – binaries: close – stars: individual: 4U 1636−53 – stars: neutron – X-rays: stars – X-rays: bursts

1. Introduction

The low-mass X-ray binary 4U 1636−53 was classified by Hasinger & Van der Klis (1989, hereafter HK89) as an atoll source. The HK89 classification of low-mass X-ray binaries

is based on the correlated variations of the X-ray spectral and rapid X-ray variability properties. HK89 distinguished two (sub-)types of bright low mass X-ray binaries, the Z sources and the atoll sources, whose names were inspired by the shapes of the tracks that they trace out in an X-ray colour-colour diagram on time scales of hours to days.

Atoll sources are different from Z-sources in several ways: they are less luminous, and the "horizontal branch quasi-periodic oscillations" or "normal/flaring branch quasi-periodic oscillations" seen in Z-sources have not been observed in them. The pattern traced out by an atoll source in a colour-colour diagram is usually (very) roughly U-shaped. The mass accretion rate ($\dot{M}$) and (usually) X-ray count rate increase from left to right along the U. At high $\dot{M}$ levels motion in the colour-colour diagram is relatively fast, and within several hours an upwardly curved "banana" branch is traced out. At low $\dot{M}$ levels, motion is slow, and observations lasting a few hours to a few days produce "islands" in the colour-colour diagram— this effect is probably observational, and caused by a combination of relatively slow motion in the colour-colour diagram and the limited length of the observations (HK89). When an atoll source becomes very faint more complex patterns can occur (Yoshida et al., 1993, Berger & Van der Klis, 1996).

The power spectra of atoll sources show two clear components (HK89), very low frequency noise (VLFN), most prominent in the "banana" state, and high frequency noise (HFN), most prominent in the "island" state. VLFN has a power-law shape, HFN is a band-limited noise component with a cut-off in the $5 - 50$ Hz range. A range of power spectral shapes occurs, from a banana state power spectrum that consists of purely a VLFN power law to an island state power spectrum that contains only a strong HFN component with various mixed power-spectral shapes containing both VLFN and HFN in between. In recent work (Van der Klis, 1994) it has been suggested that the prominent band-limited noise components in the power spectra of atoll sources in the island state (atoll

source HFN), black-hole candidates in the low state (low-state noise) and Z-sources in the horizontal branch (Z-source LFN) are all due to the same physical phenomenon, the accretion of inhomogeneities (clumps) in the inner disk. We will address this issue in Section 4.

Previous work on the EXOSAT data of 4U 1636−53 included several studies aimed at the burst properties (Turner & Breedon, 1984, Lewin et al., 1987, Damen et al., 1989, Damen et al., 1990), and the X-ray spectrum of the persistent emission (Breedon et al., 1986, Vacca et al., 1987). HK89 presented one colour-colour diagram and three power spectra based on part of the EXOSAT data. Van der Klis et al. (1990) discussed the relation between the colour-colour diagram and the burst properties. In this paper we present a complete and homogeneous analysis of the persistent emission in all EXOSAT data on 4U 1636−53, and investigate in detail the correlation between the power spectra and the X-ray colours.

In Section 2 we describe the observations, in Sections 3.1 – 3.3 we describe the analysis of the spectral data in terms of colour-colour diagrams and hardness-intensity diagrams, and in Section 3.4 we describe the analysis of the timing data in terms of power spectra. We discuss our findings in Section 4.

2. Observations

During the lifetime of EXOSAT 4U 1636−53 was observed for a total of 176 hours with the Medium Energy (ME) instrument (Turner et al., 1981). An overview of the available ME data, and the time and energy resolution for the different data sets can be found in Table 1. During the 1983 and 1984 observations, one half of the ME instrument was pointed at the source, while the other half was slightly tilted to monitor the background. Typically every 4 hours swaps between the halves were made. During the 1985 observations, both halves were pointed towards the source most of the time. We removed all X-ray bursts from the data using a table of burst onset times given by Damen et al. (1990). For each burst, we removed $260\,\mathrm{s}$ of data, from $10\,\mathrm{s}$ before to $250\,\mathrm{s}$ after the onset time. For background determination, we used slew data or data from offset array halves, whichever were closest in time. We used, whenever possible, only data from the argon detectors (1–20 keV), which have a better source to background count rate ratio than the xenon detectors (5–50 keV). The spectral (HER) data were always from the argon detectors, but in the case of the high-time resolution (HTR) data, sometimes only summed argon plus xenon data were available.

3. Analysis and results

3.1. Colour-colour and hardness-intensity diagrams

We constructed colour-colour diagrams and hardness-intensity diagrams using the argon-only HER data. Inspection of the spectrum of 4U 1636−53 shows, that for

energies above ~ 12 keV the spectrum is dominated by the background. For the colour-colour diagrams and hardness-intensity diagrams we therefore only used the data below 11.55 keV. We divided these data into always exactly the same four broad energy bands (see Table 2). To minimize the statistical uncertainties, the energy bands were chosen such that each band had roughly the same count rate.

Table 2. The energy bands used for the calculation of colours.

Band	Start (keV)	End (keV)
1	0.94	2.37
2	2.37	3.38
3	3.38	4.96
4	4.96	11.55

3.2. Instrumental corrections

The detector gains varied slightly over the years, resulting in changing channel energy boundaries, and the detectors were not identical in gain and response. Also, some of them broke down during the life of EXOSAT. All this resulted in different effective energy-channel boundaries in the on-board summed data from different detectors. We corrected for this by interpolating between the count rates in the original energy channels according to the instantaneous effective channel energy boundaries in such a way as to keep the effective energy bands the same. The count rates in each band were corrected for dead-time (Andrews & Stella, 1985), and background; we always used background count rates obtained from the same detectors as used for the source observation. We used these dead-time and background corrected count rates to calculate the X-ray colours. The "soft colour" is defined as the ratio of the count rate in band 2 to that in band 1, the "hard colour" is defined as the ratio of band 4 to band 3. The "hardness ratio" used in the hardness-intensity diagrams is the ratio of the summed count rate in bands 3 and 4 to the summed count rate in bands 1 and 2, and the "intensity" is the sum of the count rates from bands 1, 2, 3, and 4. We uniformly used an integration time of 200 s per point.

To correct the colours and intensity for variation in the instrumental response (as opposed to variations in effective energy boundaries), we calculated colour-colour diagrams and hardness-intensity diagrams of the Crab Nebula using the same energy bands and analysis methods as for 4U 1636−53. This procedure is described in more detail in Kuulkers et al. (1994). We found that the difference between the two halves of the EXOSAT ME instrument caused by the different detector responses is $\sim 1\,\%$ in the case of the soft colours, and only $0.2\,\%$ for the hard colours. From year to year the changes in the colours of the Crab

Table 1. List of pointed observations of 4U 1636−53 with the EXOSAT ME instrument. In Columns 1 through 4 the observation start and end time and date are given. Column 5 gives the On Board Computer programs that were running, Columns 7 and 9 give the time resolutions of the energy (7) and timing (9) data respectively. In Columns 6 and 8 a specification of the data is given, Ar denotes that data from the argon chambers (1-20 keV) only were used, Ar+Xe denotes that summed data from argon and xenon chambers (5-50 keV) were used. SB denotes one half on source, and one half on the background, SS denotes that both halves were on source most of the time (SSSS denotes that data were available for individual array quadrants, and that all quadrants were on source most of the time). In Columns 10, 11, and 12 information about the available energy channels for the HER data is listed: 10 begin channel, 11 end channel, 12 compression factor. References in the last column refer to 1) Damen et al., 1989, 1990, 2) HK89, 3) Lewin et al., 1987, 4) Vacca et al., 1987, 5) Turner & Breedon, 1984

EXOSAT ME observations of 4U 1636−53												
Observation date and time (UT)				OBC programs	HTR data	Time resolution	HER data	Time resolution	Start chan.	End chan.	Comp. factor	Refs.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1983	July	17 17:57	18 05:21	E4, E5, T3	Ar	7.8125 ms	SB	0.3125 s	0	63	2	1,5
1984	May	6 01:24	6 20:14	E5	n/a	n/a	SB	0.3125 s	4	67	2	1, 4
1984	May	8 11:04	9 10:00	E5, T3	Ar	7.8125 ms	SB	0.3125 s	4	67	2	1, 4
1984	Sep	7 05:15	7 14:41	E5, T3	Ar	7.8125 ms	SB	0.625 s	4	67	1	1
1985	Aug	6 19:23	7 01:42	E5, T3	Ar	1.9531 ms	SS	1.0 s	4	67	1	1, 2, 3
1985	Aug	7 11:10	10 17:50	E5, T3	Ar+Xe	7.8125 ms	SS	0.3125 s	4	67	2	1, 2, 3
1985	Aug	11 09:21	11 10:50	E4, T3	Ar+Xe	31.25 ms	SSSS	10 s	4	67	1	1
1985	Sep	5 06:20	6 05:56	E5, T3	Ar+Xe	31.25 ms	SS	0.3125 s	4	67	1	1
1985	Sep	6 16:16	6 20:10	E5, T3	Ar+Xe	31.25 ms	SS	0.3125 s	4	67	1	1

Fig. 1. Corrected X-ray colour-colour diagrams of 4U 1636−53. Soft colour is defined as the ratio of the 2.4–3.4 keV band to the 0.94–2.4 keV band, hard colour as the ratio of the 5.0–11.6 keV to the 3.4–5.0 keV band. Each point represents a 200 second integration. a) corresponds to July 1983, b) May 1984, c) September 1984, d) August 1985, e) September 1985. Typical error bars are shown

Fig. 2. Corrected X-ray hardness-intensity diagrams of 4U 1636−53 for the different data sets. Hardness is defined as the ratio of the summed count rates in the 3.4–11.5 keV band to the count rates in the 0.94–3.4 keV band, intensity as the count rate (counts/sec/cm^2) in the 0.94–11.6 keV range. Each point represents a 200 second integration. a) corresponds to July 1983, b) May 1984, c) September 1984, d) August 1985, e) September 1985. Typical error bars are shown

Nebula were usually about 0.5%. On two occasions we found larger deviations: +1.2% in soft colour and −1.3% in hard colour in 1983, and −1.3% in soft colour in 1985. The change in 1985 can be fully ascribed due to the failure of detector 3. The changes in intensity of the Crab Nebula range from +4% to −3%. We corrected the colours and intensities of 4U 1636−53 for these yearly variations and for the differences in detector responses between the two halves by assuming that the same effects as seen in the Crab Nebula also apply to 4U 1636−53. Residual systematic effects can still be present, as the observations of the Crab Nebula do not coincide in time with those of 4U 1636−53, and as the spectral shapes are not the same, but based on previous experience with this method (Kuulkers et al., 1994) we expect these to be small. The corrected colour-colour diagrams and hardness-intensity diagrams of 4U 1636−53 are shown in Figs. 1 and 2.

Fig. 3. Colour-colour diagram of the August 1985 data set showing the regions adopted to define the rank numbers.

3.3. Motion in the colour-colour plane

For each data set a pattern appears in the colour-colour diagram and hardness-intensity diagram that resembles those of other data sets. However, even after the corrections we made for instrumental effects, there is in general no exact correspondence between the colour-colour diagrams and hardness-intensity diagrams of the different observations: there are shifts in the patterns from year to year. Similar results were previously obtained for Z-sources (Kuulkers et al., 1994), and in the following we assume that it is useful to describe the behaviour of the atoll source 4U 1636−53 in the colour-colour plane in terms of a pattern with an approximately stable shape that is traced out on time scales of hours to days, which moves through the plane on longer time scales. We will discuss below to what extent this motion is intrinsic.

We used the colour-colour diagram for the August 1985 data set, which has the best statistics and the greatest variety in source behaviour, to define the motion in the colour-colour plane. As can be seen in Fig. 1, the only separate region in the colour-colour diagram of this obser-

Fig. 4. Burst duration vs. temperature for all bursts seen in 4U 1636−53 with EXOSAT. This figure is adapted from Fig. 2 in Damen et al. (1989). The filled symbols are for the September 1984 data

vation is the patch in the upper left section of the diagram, which on the basis of its power spectrum, we identify as an island (see below). The gap between the island and the rest of the colour-colour diagram is observational; due to an Earth occultation no data were obtained for eight hours, during which time the source moved considerably in the colour-colour diagram.

The only data set that matches the August 1985 colour-colour diagram without shifts is the September 1985 one. Shifts of −3 % in soft and +5 % in hard colour are needed to fit the May 1984 observation, which clearly shows a middle and upper banana, onto the August 1985 banana. The intensity in the 0.9 – 11.6 keV range of 4U 1636−53 in this observation is ~22 % lower than during the corresponding parts of the August 1985 observation. The July 1983 observation, which we identify as being entirely island-state, needs an +8 % shift in soft colour and +2 % in hard colour to make it correspond to the August 1985 island. As previously reported (Breedon et al., 1986) the flux during this observation is high and rising; it is 68 % – 125 % higher than the August 1985 island state intensity (in the 0.9 – 11.6 keV range).

For the brief September 1984 observation the state cannot be ascertained purely on the basis of the morphology of the colour-colour diagram. Therefore, we compared the properties of the three bursts seen in this observation to those of the other bursts of 4U 1636−53 using the results of Damen et al., 1989, as burst duration and temperature are known to correlate to the state 4U 1636−53 (Van der Klis et al., 1990) is in. To this purpose we have reproduced Fig. 2 from Damen et al. (1989) with different symbols for different states and different observations (see Fig. 4). From this comparison it is evident that the September 1984 data correspond to the lower banana. This implies a shift of −4 % in soft colour and +4 %in hard colour, and −19 % in intensity in the 0.9 – 11.6 keV range with respect to the August 1985 data.

The observed changes in the colours and intensities of 4U 1636−53 are much larger than the observed changes in the colours and intensities of the Crab Nebula. Also, the direction of the changes in colours and intensities of 4U 1636−53 and the Crab Nebula are not always the same.

Fig. 5. Colour-colour diagram of the May 1984 data with the rank number regions superimposed. Closed symbols refer to observations where simultaneous HTR data are available, open symbols where HTR data are missing.

For the purpose of quantifying the position of the source in the pattern in the colour-colour diagram, we divided the colour-colour plane into eight regions, numbered from 1 to 8 (see Fig. 3). The August 1985 island corresponds to region 1, and the remaining wedge-like regions divide the August 1985 banana into 7 sections, numbered 2 to 8. The position of the source in the pattern is now defined by the number of the region in the colour-colour diagram it is in after all the shifts needed to make the pattern coincide with the August 1985 one were made. We shall refer to this number as the "rank number" from now on. In this way the May 1984 observation ranks $2 - \gtrsim 8$, the September 1984 observation 5, and the September 1985 observation $7 - 8$

Only in the case of the July 1983 observation we think that its colour-colour diagram cannot be shifted onto the August 1985 colour-colour diagram, since we suggest it corresponds to a state not present in the August 1985 observation (see Section 4) . We have divided the July 1983 data set in two parts, corresponding to the two features in the hardness-intensity diagram separated at intensity $0.195 \, \mathrm{c/s/cm^2}$ (one part bent upward to the left, the other part horizontal). We have assigned these rank numbers 0 and 0.5 . In Fig. 4 it can be seen that the bursts during this observation have the most extreme values of all bursts of 4U 1636−53 that were observed by EXOSAT.

3.4. Power spectra

We calculated power spectra from the 7.8 ms and 1.9 ms HTR data (see Table 1) using a time resolution of 7.8 ms throughout. We used data stretches with a length of 256 s each containing 32768 points, so the resulting power spectra range from 1/256 Hz to 64 Hz. All incomplete time series (due to satellite telemetry drop outs, array swaps or burst removal) were removed from the analysis. This implied a loss of 10–25 % of the data, depending on observation. As longer data stretches would have resulted in more data loss, we stuck with a length of 256 s and thus a lowest frequency of 0.0039 Hz, even though an extension to lower frequencies might have been of interest. The 31.25 ms data were analyzed separately: only in this case we calculated power spectra from data stretches of 1024 s each containing 16384 points.

We subtracted the predicted Poisson level as altered by dead time processes from each power spectrum using expression 3.9 from Van der Klis (1989) with an effective deadtime of 10.6 μs (Berger & Van der Klis, 1994), and then averaged the (Leahy-normalized) power spectra according to rank number. Usually, more than 50 power spectra were averaged. Power spectra of time series which overlap with more than one region in the colour-colour diagram contribute to the average proportionally to the fractional extent of the overlap.

We fitted the power spectra using a function consisting of two components, very low frequency noise (VLFN) de-

Fig. 6. The power spectra with best fits for the different rank numbers in the colour-colour diagrams of August 1985. The contribution of the EXOSAT ME intrinsic band limited noise (Berger and Van der Klis, 1994) is also plotted

Fig. 7. The power spectra for the different rank numbers in the colour-colour diagrams of July 1983, May 1984, September 1984, and September 1985. The contribution of the EXOSAT ME intrinsic band limited noise (Berger and Van der Klis,1994) is also plotted

Table 3. List of fit parameters for power spectra of 4U 1636−53. In Column 2 the rank number is given. Columns 3 through 6 give VLFN fit results: 3 rms, 4 rms error, 5 power law index, 6 index error. Columns 7 through 12 give HFN fit results: 7 rms, 8 rms error, 9 power law index, 10 index error, 11 cut-off frequency, 12 frequency error. In Columns 13 and 14 we list the χ^2, and the degrees of freedom. In Columns 15 and 16 we list the summed total count rate per sec and summed back ground count rate per sec, as well as the ratio of number of detectors on source to total number of available detectors. For all power spetral fits the VLFN rms was integrated over $0.01 - 1$ Hz. For the July 1983, May and September 1984, and August 1985 power spectral fits the HFN rms over $0.1 - 64$ Hz. Only for the September 1985 power spectral fits the HFN rms was integrated over $0.1 - 16$ Hz. The listed errors are based on a scan in χ^2 space using $\Delta\chi^2 = 1$; – denotes that this parameter was kept fixed

Obs	RN	VLFN				HFN						χ^2	DOF	Count	Back
		rms %	error	index	error	rms %	error	index	error	ν_{cut} (Hz)	error			rate	ground
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
85 Aug	1	0	− −	1.30	− −	7.84	+0.75 −0.76	−0.30	+0.19 −0.27	10.2	+4.6 −3.0	37.0	34	254.8 8/8 Ar	92.0
	2	2.77	+0.32 −0.37	1.30	− −	14.64	+1.26 −1.37	−0.64	+0.29 −0.40	28.9	+25.3 −10.1	49.7	33	794.0 8/8 Ar+Xe	620.0
	3	1.63	+0.24 −0.23	2.19	+0.33 −0.28	9.25	+0.83 −0.92	−0.26	− −	100	− −	29.9	34	848.7 8/8 Ar+Xe	620.0
	4	0.94	+0.17 −0.21	1.30	− −	4.45	+1.09 −1.47	−0.26	− −	100	− −	22.5	35	890.1 8/8 Ar+Xe	620.0
	5	1.66	+0.28 −0.29	1.22	+0.21 −0.17	1.45	+2.05 −4.29	−0.26	− −	100	− −	28.7	34	928.5 8/8 Ar+Xe	620.0
	6	2.31	+0.17 −0.17	1.33	+0.11 −0.10	2.04	+1.49 −4.07	−0.26	− −	100	− −	33.1	34	975.1 8/8 Ar+Xe	620.0
	7	2.50	+0.14 −0.14	1.34	+0.08 −0.07	3.08	+1.03 −1.63	−0.26	− −	100	− −	31.0	34	1007.7 8/8 Ar+Xe	620.0
	8	2.30	+0.15 −0.15	1.42	+0.09 −0.09	−1.36	+3.80 −1.74	−0.26	− −	100	− −	35.4	34	1032.8 8/8 Ar+Xe	620.0
83 Jul	0.0	0	− −	1.30	− −	10.53	+0.94 −0.97	−0.21	+0.19 −0.26	12.9	+6.4 −4.0	23.4	34	224.6 4/8 Ar	92.0
	0.5	1.45	+0.18 −0.20	1.30	− −	9.63	+0.71 −0.76	−0.49	+0.29 −0.41	18.9	+10.8 −5.7	40.8	33	262.0 4/8 Ar	92.0
84 May	2.75	1.28	+0.31 −0.41	1.30	− −	7.92	+1.52 −1.90	−0.26	− −	100	− −	33.2	35	190.9 4/8 Ar	92.0
	3.25	1.47	+0.22 −0.25	1.30	− −	2.91	+2.34 −6.17	−0.26	− −	100	− −	33.4	35	193.7 4/8 Ar	92.0
	3.75	1.43	+0.21 −0.24	1.30	− −	−3.56	+6.05 −2.06	−0.26	− −	100	− −	34.6	35	199.0 4/8 Ar	92.0
	4.25	0.72	+0.37 −1.12	1.30	− −	6.01	+1.78 −2.62	−0.26	− −	100	− −	45.5	35	204.5 4/8 Ar	92.0
84 Sep	5	1.73	+0.28 −0.28	1.45	+0.25 −0.20	5.62	+1.11 −1.39	−0.26	− −	100	− −	42.3	34	213.0 4/8 Ar	92.0
85 Sep	7	2.57	+0.16 −0.22	1.33	+0.11 −0.08	1.86	+0.74 −1.63	+0.17	+0.30 −0.44	10000	− −	17.8	29	890.5 7/7 Ar+Xe	541.0
	8	2.11	+0.19 −0.23	1.53	+0.16 −0.12	2.58	+0.54 −0.70	+0.35	+0.18 −0.21	10000	− −	33.0	29	906.0 7/7 Ar+Xe	541.0

scribed by a power law, and high frequency noise (HFN) described by a power law with an exponential cut-off (HK89). In a number of cases we found that the five-parameter fit function was not sufficiently constrained by the data to determine all parameters. In particular, the HFN cut-off frequency was usually not well-constrained when it was near or beyond the Nyquist frequency. Also, the HFN power-law index was in those cases usually hard to measure. For rank numbers $\gtrsim 4$ the HFN component was hardly measurable above the EXOSAT ME intrinsic band limited noise reported by Berger and Van der Klis (1994). Therefore, for rank numbers > 2 we fixed the HFN cut-off frequency and the power-law index at the values found by Berger and Van der Klis (1994) for the intrinsic noise, leaving only the strength of the HFN as a fit parameter. For most power spectra for rank numbers $\lesssim 4$ the VLFN power-law index was difficult to measure. In those cases we fixed the power-law index at a value representative of that seen in other power spectra.

For the September 1985 power spectra the Nyquist frequency is only 16 Hz. Therefore, we only tried to measure the strength of the HFN by fixing the cut-off frequency at a high value.

To all fractional rms amplitudes derived from the fits we applied a correction factor $(B + S)/S$, where B is the background count rate and S the source count rate, so as to obtain the fractional rms amplitude of the source flux. This background correction factor amounts to ~ 1.54 to ~ 1.93 for the data that consisted of argon only, and ~ 2.48 to ~ 4.56 for the data that consisted of argon plus xenon (due to the higher background for the xenon detectors). We corrected the rms values for the presence of the EXOSAT ME intrinsic band limited noise reported by Berger and Van der Klis (1994).

For presentation purposes, we normalized the average power spectra according to the $(\mathrm{rms/mean})^2/\mathrm{Hz}$ normalization (see Van der Klis (1995) for the formulae used), so that the integrated power directly corresponds to the source fractional rms amplitude squared. The power spectra corresponding to the various colour-colour regions of the August 1985 observation are shown in Fig. 6; the power spectra of the other observations in Fig. 7. The best fit to the power spectrum, and the contribution of the EXOSAT ME instrumental component, as well as date, rank number and detectors used (argon or argon plus xenon) are shown in each diagram.

In Table 3 we list all the fit results with errors based on a scan in χ^2 space using $\Delta\chi^2 = 1$. The reason that the May 1984 observations in Table 3 only cover rank numbers $2 - 5$, whereas its colour-colour diagram clearly extends to the upper banana (even beyond rank number 8), is that for the HER data obtained for ranks $\lesssim 6$ there were no simultaneous HTR data (see Fig. 5). For all power spectral fits the VLFN rms was integrated over $0.01 - 1$ Hz. For the July 1983, May and September 1984, and August 1985 power spectral fits the HFN rms was integrated over 0.1

– 64 Hz. Only for the September 1985 power spectral fits the HFN rms was integrated over $0.1 - 16$ Hz.

Fig. 8. VLFN and HFN fractional rms amplitudes vs. rank number. Closed symbols refer to argon plus xenon data, open symbols to argon-only data.

4. Discussion

The analysis described in the previous section now enable us to answer the question to what extent the position in the pattern in the colour-colour diagram completely determines the character of the rapid X-ray variability. In Fig. 8 the fractional rms amplitudes of the VLFN and HFN are plotted as a function of rank number. Open symbols refer to argon-only data, whereas filled symbols are for argon plus xenon data. There is a clear trend of the HFN rms dropping with rank, from as high as 10–15 % at rank 1 and 2 to consistent with zero in the upper banana. The VLFN is weak ($\sim 1\,\%$) at low rank and increases to $\sim 2.5\,\%$ in the upper banana. Comparing the argon and argon plus xenon data, there is no strong evidence for a simple photon energy dependence, except perhaps for a slightly lower HFN in argon plus xenon in the lower ranked regions.

The correspondence between the various observations is good: the same trends are seen in independent data sets. When comparing the argon-only and the argon plus xenon data separately, there are no significant deviations from a smooth dependence of rms on rank in either VLFN or HFN. The HFN cut-off frequency (not plotted) was only measurable for ranks ¡ 3, where on two different occasions it seemed to increase from ~ 10 to ~ 25 Hz. There is no strong evidence for a dependence of the VLFN or HFN power-law indices with rank number.

The 1983 island state power spectra both have a higher HFN rms than the 1985 island state power spectrum. As the 1983 island state is different from the 1985 island state in terms of the burst behaviour (see Fig. 4), we believe the colour difference may be intrinsic as well. In 4U 1608−52 (Yoshida et al., 1993) and 4U 1705−44 (Berger & Van der Klis, 1996) the most extreme island behaviour occurs at the upper right of the colour-colour diagram, with less extreme island behaviour occurring at the lower left of the colour-colour diagram. We suggest that the 1983 island state is a case of an extension to the island state as described by HK89 in the direction of the (hard) upper right towards extreme island behaviour. Hence, the difference in the colour-colour diagram of 1983 should be primarily ascribed to a different state, and not to a change of the position of the island state pattern in the colour-colour diagram. The observed changes in the other data sets are also larger than the first order correction we applied, but systematic effects may still be present.

In the case of the August 1985 observation we find a high value for the HFN and VLFN rms at rank number 2, i.e., immediately after the observational gap between the island and lower banana state. In August 1985 we measure a higher HFN rms at rank number 2, than for (island) rank numbers 1 (1985) and 0 and 0.5 (July 1983). A caveat is that the rms values for rank numbers 0 – 1 were all obtained from argon-only data, whereas those for the August 1985 rank numbers 2 – 8 were from combined argon and xenon data. For rank numbers ¿ 2 the HFN rms rapidly decreases to a level consistent with zero. At rank number 2 there is still a measurable HFN cut-off frequency, which is clearly higher than for the island state. For rank numbers 2 – 4 the VLFN rms decreases, after which it rises again for rank numbers 4 – 7 , with perhaps a flattening for rank number 8. The VLFN and HFN rms values obtained for the September 1985 observation (rank number 7 – 8) are fully consistent with those of rank number 7 – 8 for the August 1985 observation.

Although the transition from low state to high state is not as gradual as had previously been suggested by HK89, their general ideas (–the spectral and the timing properties are correlated and governed by one parameter, the instantaneous mass accretion rate, –the HFN decreases in strength from low (island) state to high (banana) state, –the VLFN increases in strength from low state to high state) still hold. It is not clear however, how the non-monotonicity in the HFN and VLFN can be explained. As yet it is unclear what causes the observed high rms in both the HFN and VLFN at the transition from the island to the banana state.

In a recent paper Van der Klis (1994) argues that the HFN of atoll sources is similar to the noise of black hole candidates in the low state, while very different from the HFN of Z-sources. This indeed seems to be the case, at least for the low (island) state: in 4U 1636−53 the low state HFN decreases while its cut-off frequency increases, just as is observed from the band-limited noise in black hole candidates (Belloni & Hasinger, 1990, Van der Klis, 1994, Méndez & Van der Klis, 1996). The only atoll source in which this has been observed so far is 4U 1608−52 (Yoshida et al., 1993), but in that case at a much stronger fractional rms.

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